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13. ABSTRACT (Maximum 200 Words) The millimeter-wave (MMW) and terahertz (THz)-regime portions of the electromagnetic spectrum have enormous application potential, including high-data-rate communications, remote sensing and threat detection, high resolution radar, biomedical imaging, and spectroscopic analysis. To exploit this potential, new sources of coherent electromagnetic radiation are needed in the frequency range of 100 - 1000 GHz. The ideal source would provide high power with high efficiency in a compact, lightweight, and low-cost package. Many of the applications require bandwidths of several percent (relative) or greater and both amplifiers and oscillators are needed. Vacuum electronic devices, such as traveling wave tubes (TWTs), meet many of these requirements but are constrained by complex fabrication methods that become impractical at frequencies of ~ 100 GHz and above. This research is investigating new methods for TWT fabrication derived from semiconductor microfabrication technologies. Various microfabrication techniques are under investigation, to identify those that are optimally suited. One critical piece of research is to measure the passive microwave losses of a 400 GHz waveguide made by these microfabrication methods. The final goal includes a study of the characteristics of a microfabricated TWT using a new electron-beam source designed for MMW and THz-regime vacuum device research.				
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ANNUAL TECHNICAL PROGRESS REPORT

**“Microfabricated Traveling Wave Tubes for High
Power Millimeter-Wave and THz-regime Sources”**

AFOSR GRANT FA9550-05-1-0147

FINAL TECHNICAL REPORT

20061212241

Abstract

The millimeter-wave (MMW) and terahertz (THz)-regime portions of the electromagnetic spectrum have enormous application potential, including high-data-rate communications, remote sensing and threat detection, high resolution radar, biomedical imaging, and spectroscopic analysis. To exploit this potential, new sources of coherent electromagnetic radiation are needed in the frequency range of 100 – 1000 GHz. The ideal sources would provide high power with high efficiency in a compact, lightweight, and low-cost package. Many of the applications require bandwidths of several percent (relative) or greater and both amplifiers and oscillators are needed. Vacuum electronic devices, such as traveling wave tubes (TWTs) meet many of these requirements but are constrained by complex fabrication methods that become impractical at frequencies of ~ 100 GHz and above. This research is investigating new methods for TWT fabrication, derived from semiconductor microfabrication technologies. Various microfabrication techniques are under investigation, to identify those that are optimally suited. One critical piece of research is to measure the passive microwave losses of a 400 GHz waveguide made by these microfabrication methods. The final goal includes a study of the characteristics of a microfabricated TWT using a new electron-beam source designed for MMW and THz-regime vacuum device research

Results

Microfabricated TWTs

We have completed and perfected a process to fabricate THz-regime dimensioned folded waveguide circuits using deep reactive ion etching (DRIE) of silicon. Illustrative results are shown in Fig. 1, along with a University of Wisconsin logo etched in silicon that illustrates the precise micron-level feature-defining power of DRIE micromachining.

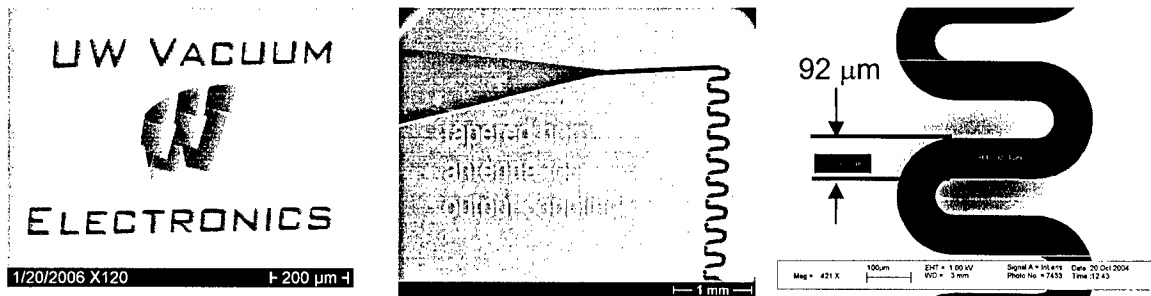


Fig. 1. Scanning electron micrograph (SEM) images of a 400 GHz folded waveguide etched with DRIE in silicon for a THz μ VED TWT. Also shown on left is an SEM of the UW logo etched in Si to demonstrate the precise features achievable with DRIE.

The final step of fabrication research is to select and validate a method to bond two wafer halves together. Wafer bonding for TWT μ VEDs requires precision alignment of two opposing wafer surfaces, followed by bonding the two halves with materials that are high-vacuum compatible. To achieve the proper alignment prior to bonding, it is necessary to use wafer backside patterning and alignment prior to bonding. We have identified a suitable and accessible facility for studying this process at the University of Minnesota. Trial experiments were conducted with a gold-silicon eutectic bonding procedure. The trial experiments revealed that the procedure needed improvements. The integrity of the gold conducting coatings elsewhere on the wafer (away from the bonding locations) were compromised, due to failure of a Cr diffusion barrier at the processing conditions (time, temperature) required for the bond. This is illustrated in Fig. 2. Subsequently, we have designed a modification to the procedure, and are conducting experiments to confirm the modifications will yield a successful wafer-wafer bond (see Fig. 3).

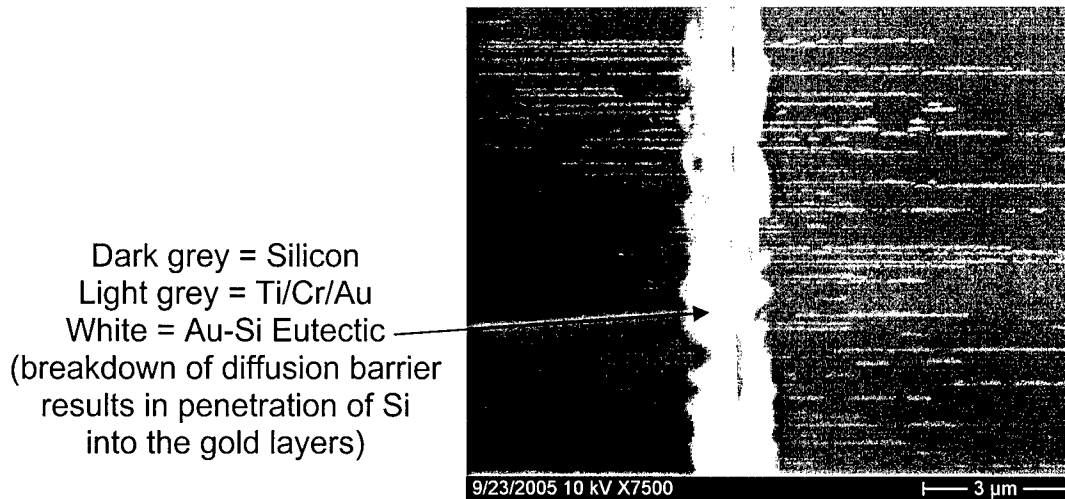


Fig. 2. SEM image showing breakdown of the Cr diffusion barrier between the Si and Au film.

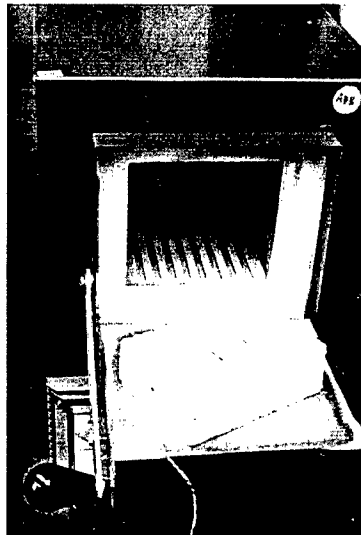


Fig. 3. Controlled process experiments will be conducted in this furnace to achieve a reliable wafer-wafer bond as the final microfabrication step for making THz-regime waveguides and μ VED THz TWT circuits.

Once the successful bond procedure is completed, we will proceed with two of the proposal objectives:

- Fabrication of 400 GHz waveguides, to make passive measurements of waveguide attenuation.
- Fabrication of 400 GHz TWTs for active device studies with the high current density ($\sim 100 \text{ A/cm}^2$) e-beam system we have assembled at UW for these types of studies.

The first study of waveguide attenuation will provide data on the effective wall conductivity of the microfabricated waveguides. Such information is crucial to reliable design of microfabricated MMW and THz-regime TWTs. The physics of ohmic losses in conducting films above 300 GHz is an important and unresolved fundamental research question, since at these frequencies the electron excursion distance during a wave cycle is very short and the classically-predicted skin depths are very small. It is expected, in fact, that at some frequency between 300 and 1000 GHz, the use of classical skin depths and ohmic dissipation will be inaccurate, and quantum mechanical methods may be required. We have procured and assembled all the instrumentation needed to make these measurements. A photograph of the setup is provided in Fig. 4. The 400 GHz power source is a Virginia Diodes 0.3 mW solid state generator, and we have several detectors, including a microwave pyrometer (shown) and a corner-cube Schottky diode detector.

This study is scheduled for completion during 2007-2008, with alternative financial support for the graduate students. Recognizing that what is needed is a fundamental, predictive theoretical understanding of effective rf conductivity from which engineers can reliably design mmwave and THz-regime devices, we have also initiated the development of a preliminary theoretical model of ohmic dissipation at THz-regime frequencies. The first realization of this model is based on Monte Carlo scattering computations, and incorporates a first approximation (semi-classical) representation of the quantum mechanical electron scattering dynamics. This model development is currently in progress, and involves a new collaboration with an assistant professor colleague in Prof. Booske's ECE Department who is expert in computational modeling of solid state electronic properties.

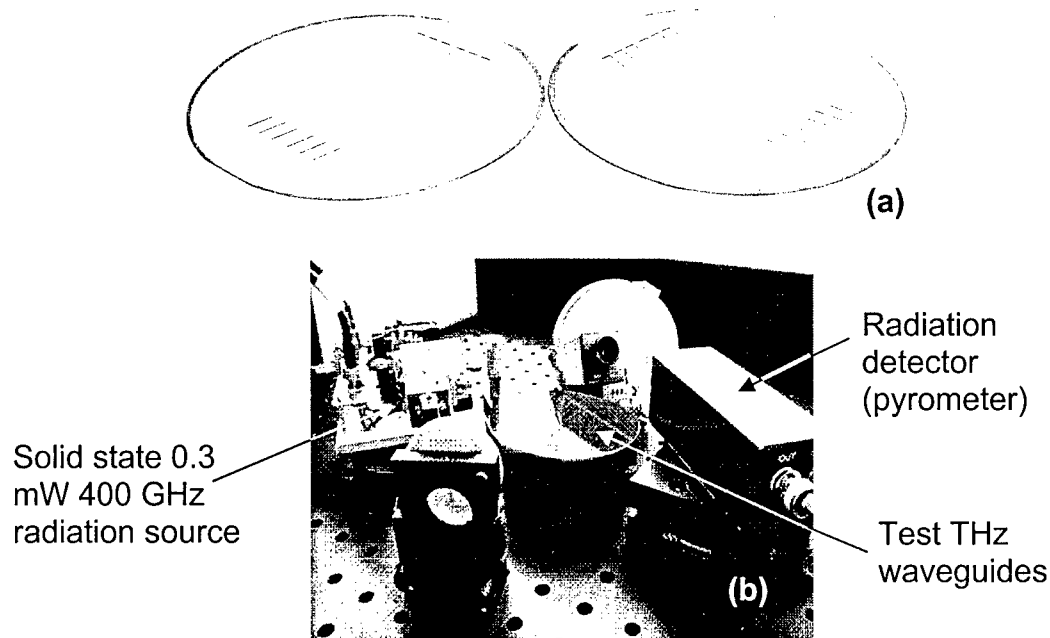


Fig. 4. (a) illustration of two metallized wafers containing DRIE fabricated 400 GHz half-waveguides. Full waveguides will be made by aligning and bonding the two waveguide halves together. (b) Configuration that will be used to measure the waveguide attenuation in the structures of Fig. (a) at 400 GHz.

Microfabricated dielectric waveguides and tapered rod antennas

A very important component to the success of MMW and THz-regime μ VEDs is finding methods for low-loss, efficient input-output coupling. We are conducting research on several approaches to this challenge. First, we are researching the prospects for micromachined precision dielectric waveguides and tapered rod high-gain antennas using low-loss (intrinsic) silicon. Fig. 5 shows the results of HFSS simulations showing how a piece of low-loss silicon can be inserted into the end of a w-band waveguide and achieve low-reflection transport of a wave at ~ 100 GHz. Figure 6 shows how a tapered version of the silicon dielectric waveguide performs as a very high gain, low-reflection MMW antenna. It is expected that these same properties would apply to components with smaller dimensions suitable for usage in the THz-regime (above 300 GHz).

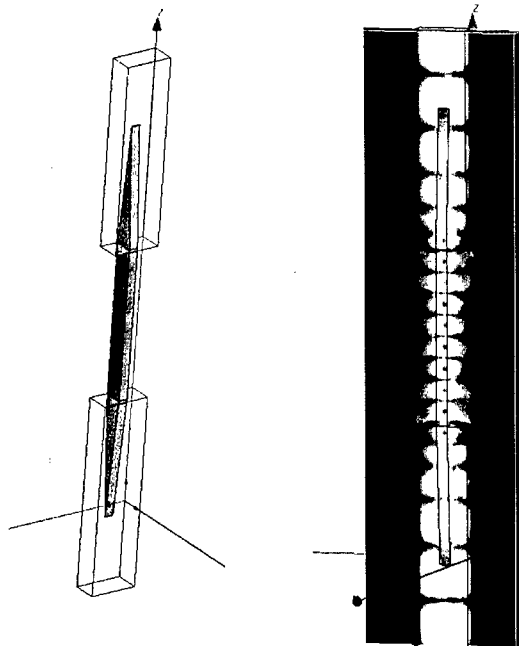


Fig. 5. Results of HFSS simulation illustrating how one can efficiently transfer a 95 GHz wave from a conventional (metal) waveguide to a low-loss silicon dielectric waveguide. This approach suggests interesting possibilities for MMW and THz-regime waveguides, vacuum windows, and compact antennas using micromachined Si.

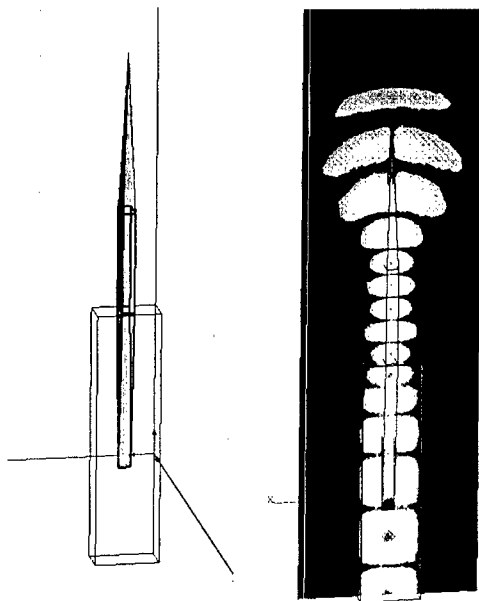


Fig. 6. Results of HFSS simulations showing that a tapered dielectric rod antenna made from micromachined low-loss Si could provide highly directional, compact antennas for MMW and THz-regime sources.

These simulation results imply that by using precise positional and reaction-rate controls, one could, in principle, precision-etch compact silicon waveguides and antennas for MMW and THz-regimes. Ultimately, it is envisioned that one might be able to fabricate both the interaction circuit and waveguide feed and antenna on the same silicon wafer. The use of silicon as waveguide and antenna material is attractive because the losses at

high frequencies are expected to be lower than ordinary metal-wall waveguides and because the silicon antenna dimensions would be compact. This latter characteristic is because the wavelength of an electromagnetic wave in silicon is approximately 3.5 times smaller than in free space.

We have assembled a precision-position-controlled etching experiment to test these ideas. By using precision robotic controls, we have successfully etched silicon rods to precision dimensions, including tapered rods. Examples are shown in Figs. 7 and 8.

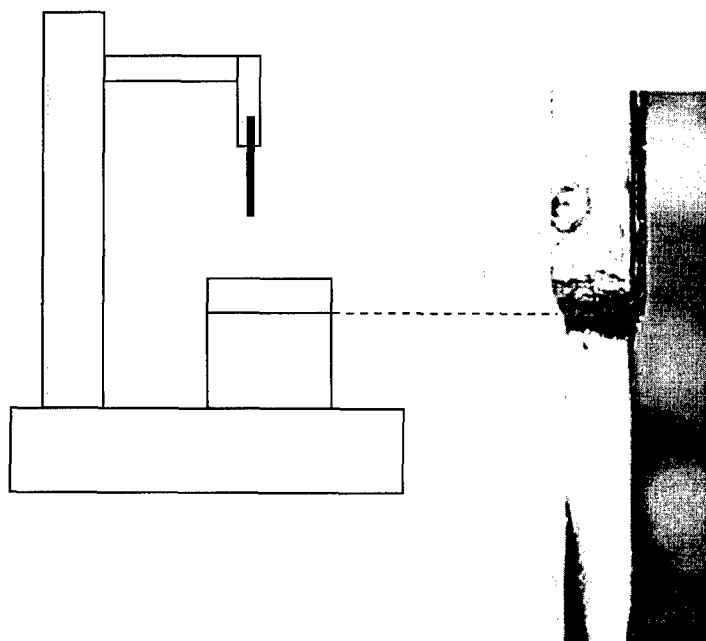


Fig. 7. Illustration of a preliminary precision etching experiment underway to evaluate the feasibility of fabricating precisely-dimensioned low-loss Si waveguides and tapered rod antennas for MMW and THz-regime applications.

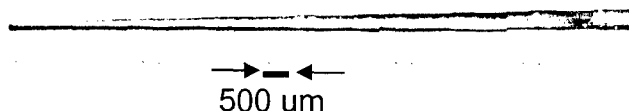


Fig. 8. Illustration of a micromachined (etched) tapered silicon rod, demonstrating the technique to be used to produce precision-dimensioned Si waveguides and rod antennas for MMW and THz-regime applications.

We have further experiments to conduct before we understand the precise chemistry involved which will allow us to control the reaction rates to achieve prescribed silicon dimensions. Subsequently, we will also conduct trial experiments of microwave waveguide and antenna transmission at W-band (80-100 GHz) and 400 GHz. In

anticipation of those proof-of-concept experiments, we have designed a simplified structure for testing at 85 GHz, using UW's 100 GHz vector network analyzer. The design of this structure was based on a narrow-band, single step taper, rather than a continuous, linear, broadband taper. The design process exploited the optimization subroutine in HFSS, and produced a step-tapered Si dielectric waveguide optimized for 100% transmission at 85 GHz. Figures 9 and 10 illustrate the transmission coefficient calculated in the vicinity of 85 GHz, showing that the transmission at 85 GHz is indeed essentially 100%, with a ~ 1.5 GHz bandwidth (estimated from the -3 dB transmission points). Figure 11 illustrates the field distribution from the simulations with this device at 85 GHz.

Additional designs of broader band structures are underway, using two-step and three-step tapers. We are also initiating an experimental fabrication of the narrow-band single step taper structure, which, when completed, will be tested in our mmwave network analyzer.

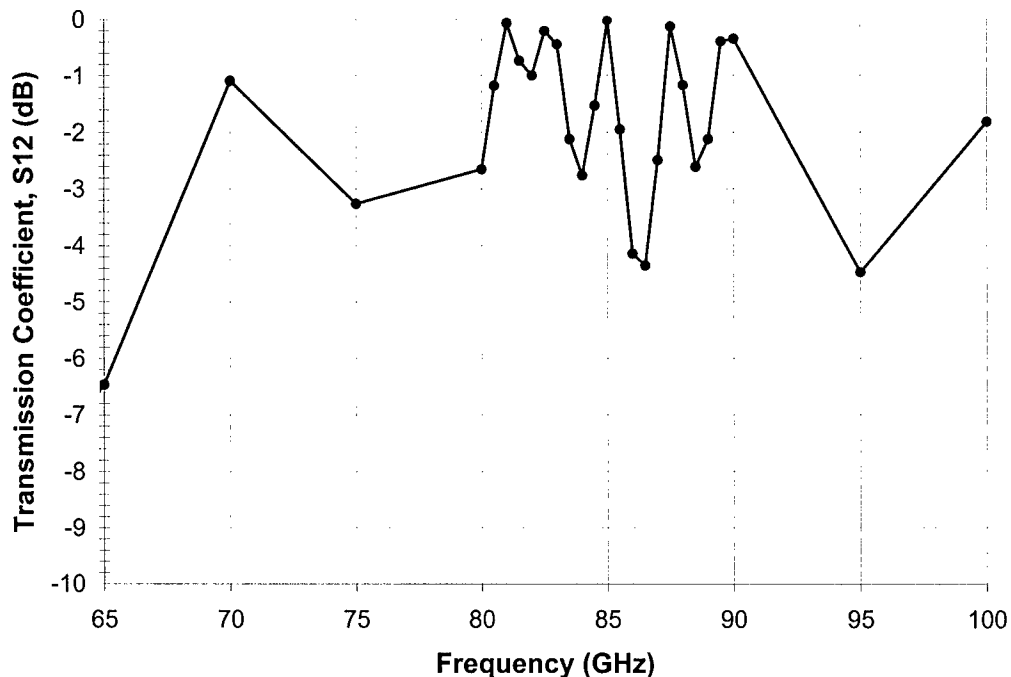


Fig. 9. Coarse frequency sweep of power transmission for narrow band, single-step tapered silicon dielectric waveguide, optimized for transmission at 85 GHz.

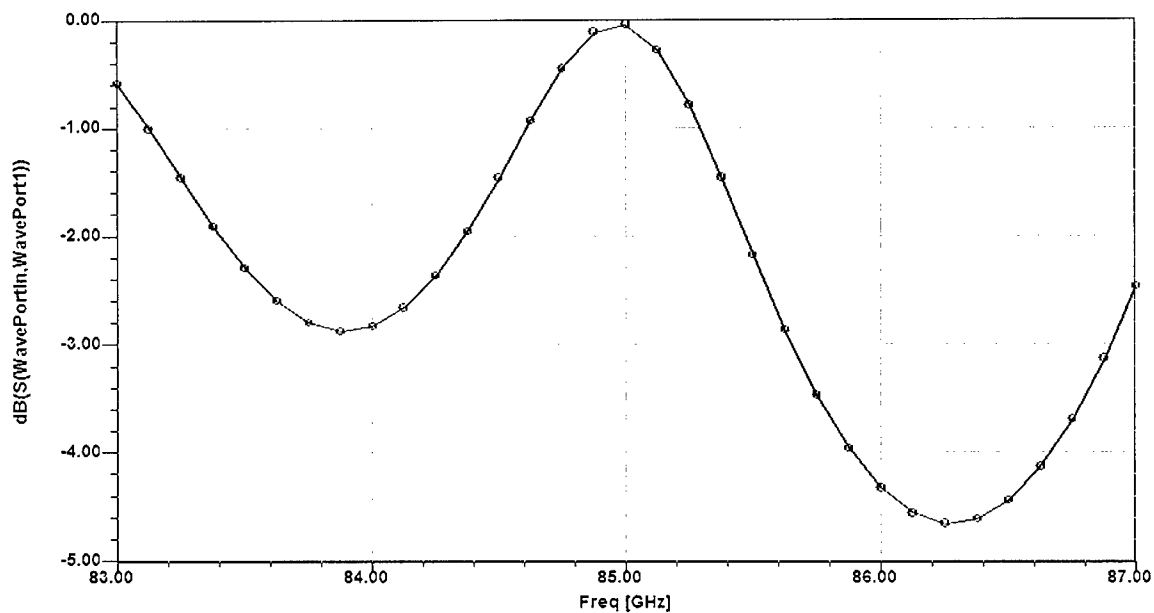


Fig. 10. Fine-resolution sweep of power transmission coefficient for single step tapered silicon dielectric waveguide that was designed for maximum transmission at 85 GHz.

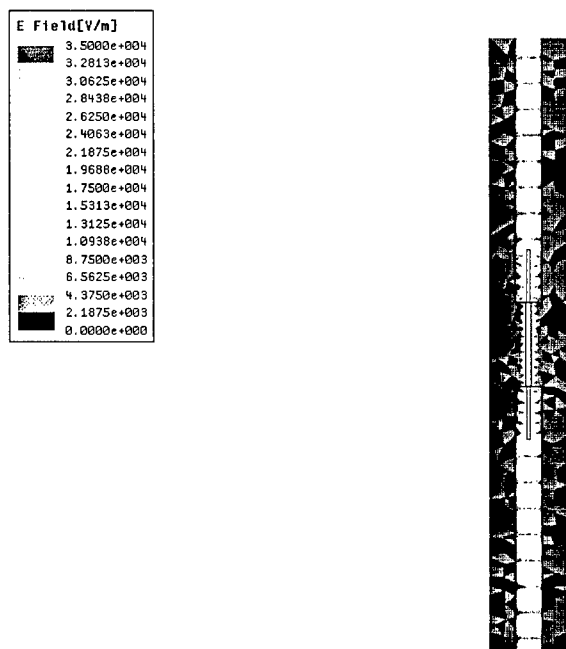
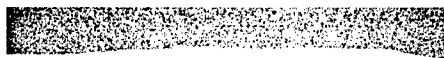


Fig. 11 Electric field distribution for the optimized case at 85 GHz.

Ultrananocrystalline Diamond (UNCD) membranes for MMW vacuum windows

We have recently initiated a collaboration between the University of Wisconsin, L3-com ED (San Carlos) and Michigan State University to study the potential of thin (less than 10 microns) ultrananocrystalline diamond membranes for MMW vacuum windows. UNCD membranes of 2 μm thickness and 2 mm diameter have been demonstrated to withstand over 5 atmospheres (80 psi) of differential pressure without rupture. This implies that they could easily hold off ultrahigh vacuum. Being very thin, their attenuation would be small and they would be unlikely to resonantly trap modes. Hence, it should not be necessary to grind them to precision thicknesses in order to achieve low-reflection transparency to MMW and sub-MMW transmission. As a first step in researching this new window material possibility, we will measure the w-band transmission characteristics of different UNCD membranes made by Michigan State University. Initial measurements revealed that conventional w-band waveguide flanges allowed for misalignment of mating flanges that placed significant stress on the membranes (causing one membrane to be broken in assembly). Moreover, conventional W-band flanges were not electromagnetically precise enough to get reliable information on the phase delay introduced by the diamond membranes. Subsequently, L3-Com ED agreed to enter into a collaboration and construct a special fixture to hold the membranes during the network analyzer measurements. This fixture eliminates the stress placed on the membranes during assembly, and also eliminates the cause of the phase delay errors of the previous, low-precision fixture.. An example of a membrane is shown in Fig. 12. An illustration of the new membrane-support fixture is shown in Fig. 13.



To: John Boske

From: Dominic Reinhard *DR*

Re: Sample SZ91

Date: July 13, 2005

Weight: 8.1 mg

Thickness (based on 9 mm diameter and 3.515 g/cm^3): 30 μm

Polishing: none

Plasma Etch: Approximately 20 micrometers were removed from the nucleation side.

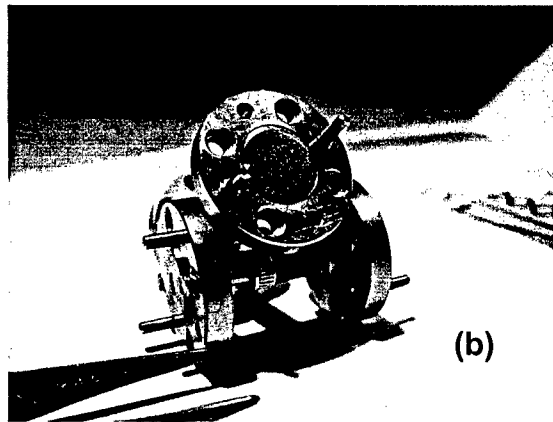
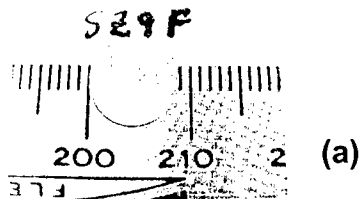


Fig. 12. (a) image of an UNCD membrane. (b) image of the membrane mounted in a W-band waveguide fixture to measure MMW transmission properties and evaluate the membranes usefulness for high power ultrathin MMW vacuum windows.

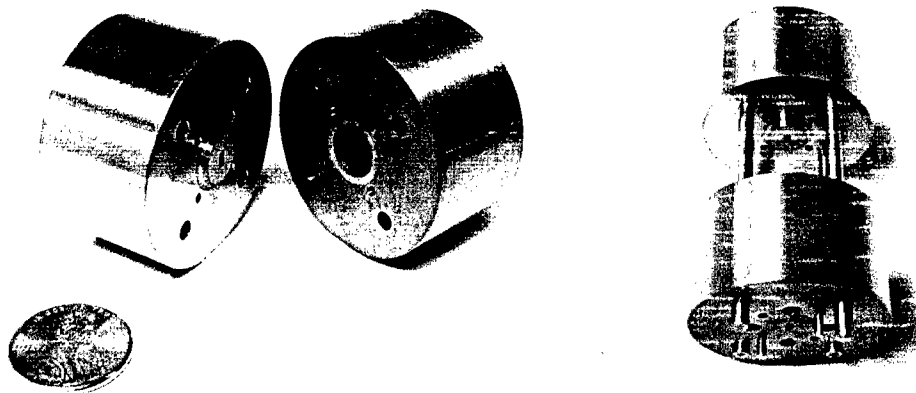


Figure 13. Images of the new fixture for measuring the millimeter-wave frequency dielectric properties of ultrathin, ultrananocrystalline diamond membranes.

A final fabrication effort is now underway, making two w-band waveguide adapters needed to complete the initial network analyzer calibration procedures before measurements of the transmission and reflection properties of the diamond membranes can proceed.

MMW and THz-regime generation by Orbitrons

With all of the current interest in compact, low-cost, efficient generators of high-power MMW and THz regime coherent generation, we recently recognized the importance of re-examining the possibilities of the orbitron, invented over 20 years ago by Dr. Igor Alexeff. Among the experiments conducted by Dr. Alexeff, one paper in particular reported generated watts of power at 1 THz. There were a number of features of Dr. Alexeff's configuration that were not ideal for a practical high frequency microwave source, including the fact that the primary source of electrons was a self-breakdown discharge plasma. However, the basic concept of the orbitron is an electrostatic equivalent to the gyrotron, and on that basis, it has inherent attractive characteristics. First, it requires no magnetic field. Second, the radiation-supporting circuit can be a quasi-optical (overmoded) cavity. Although Alexeff's group never developed an amplifier version, in principle, the concept should be amenable to either oscillator or amplifier configurations. Efficiency will be limited, but it should be able to achieve efficiencies comparable to or greater than backwards wave oscillators. Interesting questions exist on what sort of average and peak powers are attainable at MMW or THz-regime frequencies, depending on the design of the *electrostatic trap* used to induce tight-radius electron orbits. Therefore, we have designed and assembled an experiment to re-examine the orbitron for THz-regime radiation generation. Prior to beginning this project, we had extensive discussions with Dr. Alexeff, to make sure that our research plans would break new ground and not merely repeat what had already been accomplished over 15 years ago. For our experiments, the electron source will be thermionic: we will place a

heated wire parallel to the central anode wire. Figure 13 shows two views of a preliminary orbitron that we assembled and tested.

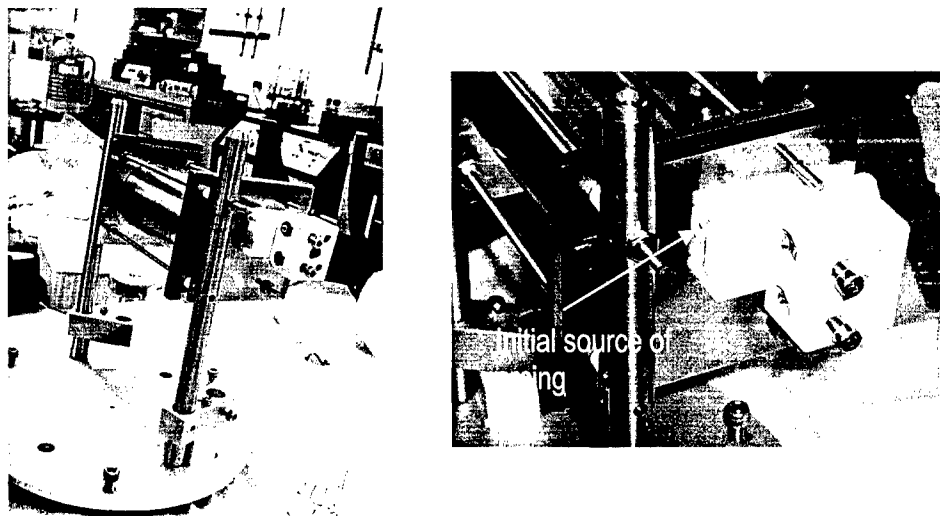


Fig. 10. Photos of the orbitron experiment currently being assembled to study the possibilities for a compact, low-cost THz-radiation source.

This initial low-cost unit introduced us to the fact that the most important engineering issue to address before fundamental physics studies could be conducted was that of arcing. In particular, we encountered arcing under cold, hi-pot testing between the high-voltage-biased cathode/filament wire and the hole that this wire passed through in the end-caps of the resonator (see arrow in Fig. 13 (b)). Subsequently, a new prototype resonator was constructed, incorporating several innovations, including a quasi-optical design that enabled confinement of the high frequency radiation while eliminating the previous cause of arcing. Indeed, this new structure was free of arcing during hi-pot testing with a cold filament. However, new sources of arcing emerged when the filament was heated to ~ 1000 C, facilitated by the thermionic electron emission. Given the multiple projects already "on our plate" and the realization that before any physics studies of advanced orbitrons could be started we were facing significant thermionic electron emission and high voltage engineering design tasks, this effort was discontinued.

Impact of grant support on students and personnel

To date, the research grant has directly or indirectly supported the research efforts and education of six students. This includes three graduate students, Sean Sengele, Al Mashal, and Ben Yang, and four undergraduate students, Amy Marconnet, Mike He, Sam Drezdson and Dan Springmann. All seven students happen to be U.S. citizens. Five of them will have received additional vacuum electronics R&D training as summer interns with L3-Com ED at San Carlos by the end of August 2006. Three faculty members and

one engineer have helped to supervise this work: Professors John Booske, Dan van der Weide, and Hongrui Jiang, and Mr. Steve Limbach, respectively.

Publications

Research contributions in three conference papers have been supported so far by this Grant.

“Microfabricated Folded Waveguide TWT circuits and components for the Terahertz and Millimeter wave regimes,” S. Sengele, J. Welter, S.-J. Ho, H. Jiang, J.H. Booske, D.W. van der Weide, S. Limbach, C.L. Kory, M.E. Read, R.L. Ives, 6th IEEE Intl. Vacuum Electronics Conference, Huis ter Duin, Noordwijk, Netherlands, 20-22 April, 2005.

“Microfabrication technologies for millimeter-wave and terahertz regime vacuum electronic devices and components,” J.H. Booske, H. Jiang, C.L. Kory, R.L. Ives, S. Sengele, D.W. van der Weide, S. Limbach, P. Borchard, Tri-Service Vacuum Electron Device Workshop, 13-15 Sept, Albuquerque, NM (2005).

“Generation of Terahertz Regime Radiation by Microfabricated Folded Waveguide Traveling Wave Tubes,” S. Sengele, H. Jiang, J.H. Booske, D.W. van der Weide, S. Limbach, A. Mashal, B. Yang, A. Marconnet, M. He, P. Larsen, IEEE International Vacuum Electronics Conference and IEEE International Vacuum Electron Sources Conference, IVEC/IVESC 2006, 25-27 April, (Monterey, CA, 2006). **Finalist selection for Best Student Paper Award.**

“Microfabricated traveling wave tubes for terahertz regime radiation sources,” S. Sengele, H. Jiang, J.H. Booske, D.W. van der Weide, S. Limbach, SPIE Defense & Security Symposium, Terahertz for Military and Security Applications IV Conference, paper 6212-08, 17-18 April (Orlando, Florida, 2006).

“Microfabrication of Terahertz Regime Folded Waveguide Traveling Wave Tubes,” S. Sengele, H. Jiang, J.H. Booske, D.W. van der Weide, S. Limbach, A. Mashal, B. Yang, A. Marconnet, M. He, P. Larsen, International Conference on Plasma Science, 4-8 June (Traverse City, MI, 2006).